<u>Phase II Topical Report for DE-FG07-99ID13778</u>
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Monitoring and Control Research Using a University Research Reactor

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<u>SUMMARY:</u> The 1999 DOE NEER-funded project on "Monitoring and Control Research Using a University Reactor and SBWR Test-Loop" has completed all of its Phase 2 goals and is ready to proceed to the next phase.

The following eight publications and presentations were made during Phase 1 [1] and 2 [2->8]:

1. R.M. Edwards. June 2000. Expansion of a Testbed for Advanced Reactor Monitoring and Control. *Trans. of the Amer. Nucl. Soc*. 82:78-80. San Diego, CA.

2. *Ceceñas-Falcón, M., and R.M. Edwards. July 2000. Stability Monitoring Tests Using a Nuclear-Coupled Boiling Channel. *Nuclear Technology*. 131:1-11.

3. Ceceñas-Falcón, M., and R.M. Edwards. November 2000. Out-of-Phase BWR Stability Monitoring. *Proceedings of The Third American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies, NPIC&HMIT'2000*. 9 pages on CD ROM. Washington, DC

4. Shyu, S., and R.M. Edwards. November 2000. Optimized-Feedforward and Robust-Feedback Used in Integrated Automatic Reactor Control. *Proceedings of The Third American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies, NPIC&HMIT'2000*. 8 pages on CD ROM. Washington, DC.

5. He, W., Z. Huang, and R.M. Edwards. November 2000. Experimental Validation of Optimized-Feedforward Control for Nuclear Reactors. *Proceedings of The Third American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies, NPIC&HMIT'2000*. 8 pages on CD ROM. Washington, DC.

6. Huang, Z., and R.M. Edwards. November 2000. Hybrid Reactor Simulation of BWR Using a First Principle Boiling Channel Model. *Proceedings of The Third American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies, NPIC&HMIT'2000*. 8 pages on CD ROM. Washington, DC.

7. Shaffer, R., W. He, and R.M. Edwards. November 2000. Experimental Validation of Robust Control for Nuclear Reactors. *Proceedings of The Third American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies, NPIC&HMIT'2000*. 9 pages on CD ROM. Washington, DC.

8. Edwards, R.M., Z. Huang, and W. He. November 2000. Integration of a Thermal-Hydraulic Test-loop and University Research Reactor for Advanced Monitoring and Control Research. *Proceedings of The Third American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies, NPIC&HMIT'2000*. 8 pages on CD ROM. Washington, DC.

The following publications were accepted or submitted during Phase 2:

9. *Ceceñas-Falcón, M., and R.M. Edwards. Application of a Reduced Order Model to BWR Corewide Stability Analysis. To appear in *Annals of Nuclear Energy*.

10. Shaffer, R., and R.M. Edwards. Design and Validation of Robust Control for Nuclear Reactors. *IEEE Transactions on Control Systems Technology*. submitted October 2000.

PHASE 2 DISCUSSION:

Two goals were defined for Phase 2, and their accomplishments are briefly discussed.

The first goal of Phase 2 (Task 5 in the 3-year project) was to evaluate an on-line uncertainty monitoring system for a robust reactor controller in the research reactor environment, Figure 1. The robust control **Performance Weighting Function** is used in an on-line filter to provide information to help determine the performance of the controller. A real-time nonlinear simulation model of the plant operates in parallel with the plant. The error signals between **Power Demand Signal** and plant output and between **Power Demand Signal** and simulated plant output are inputs to the **Performance Weighting Function** filters. Fuzzy logic is further used to process the outputs of the filters to provide a measure of the controlled system performance. Switching to predefined robust control for different operating ranges can make accommodation of anomalous events, such as excursions into different operating regions.

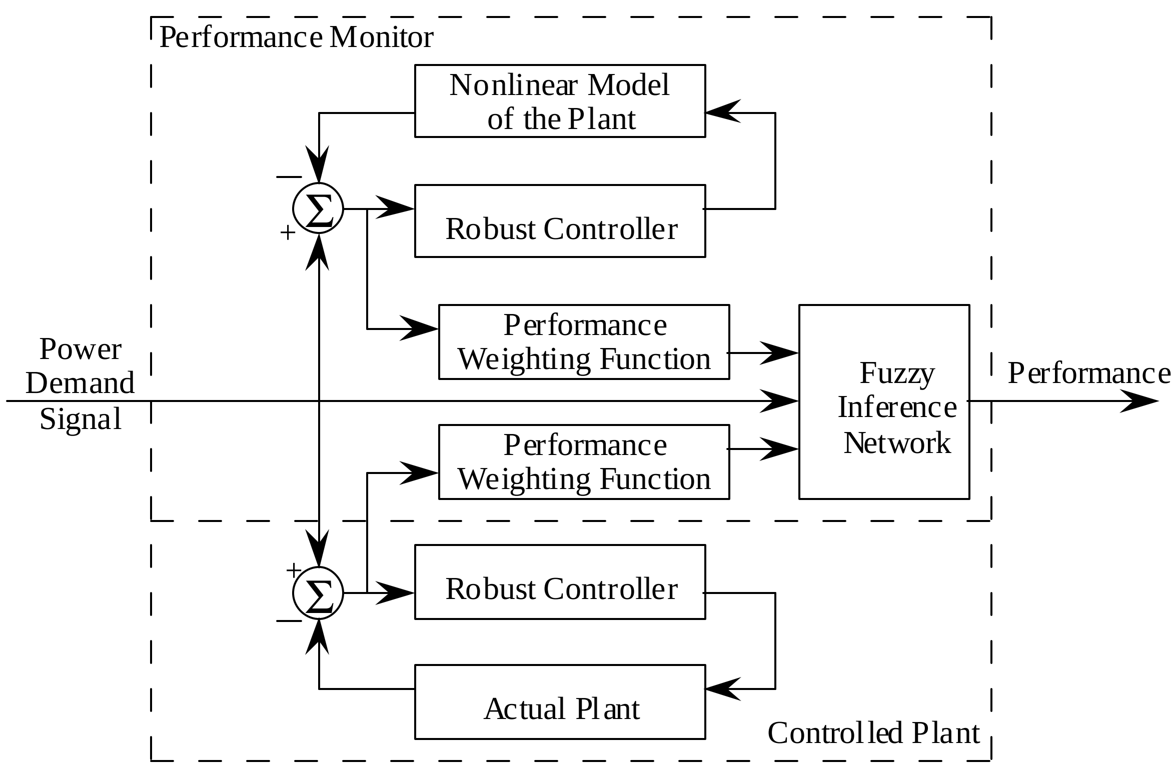


Figure 1: Robust Control Performance Monitor

TRIGA reactor experiments were conducted during Phase 2 to evaluate on-line performance monitoring techniques. New robust control designs were developed to better match experimental conditions available in the TRIGA reactor. A two-dimensional nine-region operating space is obtained by combining three operating ranges on reactor power (nr) and Reactivity Velocity Gain (Rvg). On-line performance monitoring experiments are conducted within the Mathwork's MATLAB/SIMULINK Real-time workshop environment. Figure 2 presents the top-level MATLAB/SIMULINK block diagram. The upper part is employed to control the reactor (real plant). The controller block consists of two robust controllers. The switch block is used to determine which controller is to be used. The lower part provides real-time simulation of the transient in parallel to the reactor experiment, where a nonlinear reactor model is used.

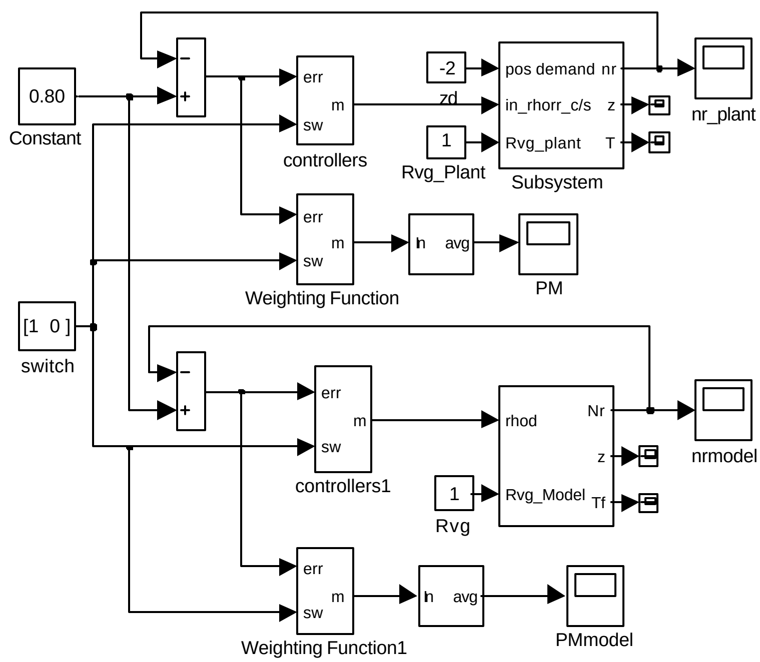


Figure 2: On-line Performance Monitoring Experiment Setup

Some experimental results are presented in Figures 3 and Figure 4. Figure 3 shows the experimental results using the controller designed for the operating range OR21, where the relative power (nr) range is from 0.7 to 1.0 and reactivity velocity gain (Rvg) range is from 0.75 to 1.25. The top two figures present the power response and corresponding output from performance monitor (PM) with Rvg=1.0. The bottom figures give the experimental results obtained with Rvg =0.5, which is out of the design range of the controller for OR21. Figure 4 presents the experimental results using the controller designed for the operating range OR31, which is defined as follows: nr=[0.7 1.0]; Rvg =[1.25 1.75]. According to these experimental results, the PM output shows a larger magnitude and a larger "pulse" width when a controller is working out of its design operating range. These robust-control performance-monitoring characteristics can be incorporated in an on-line decision making process to choose appropriate robust control selection and enforcement.

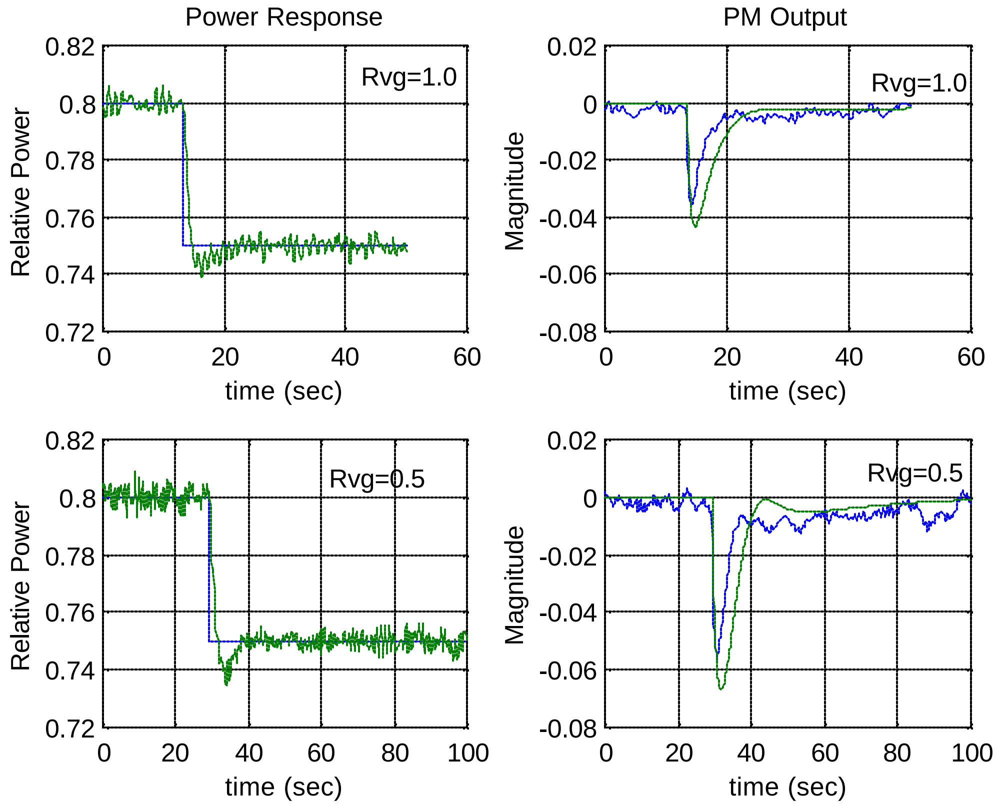


Figure 3: Experimental Results with the Controller for OR21

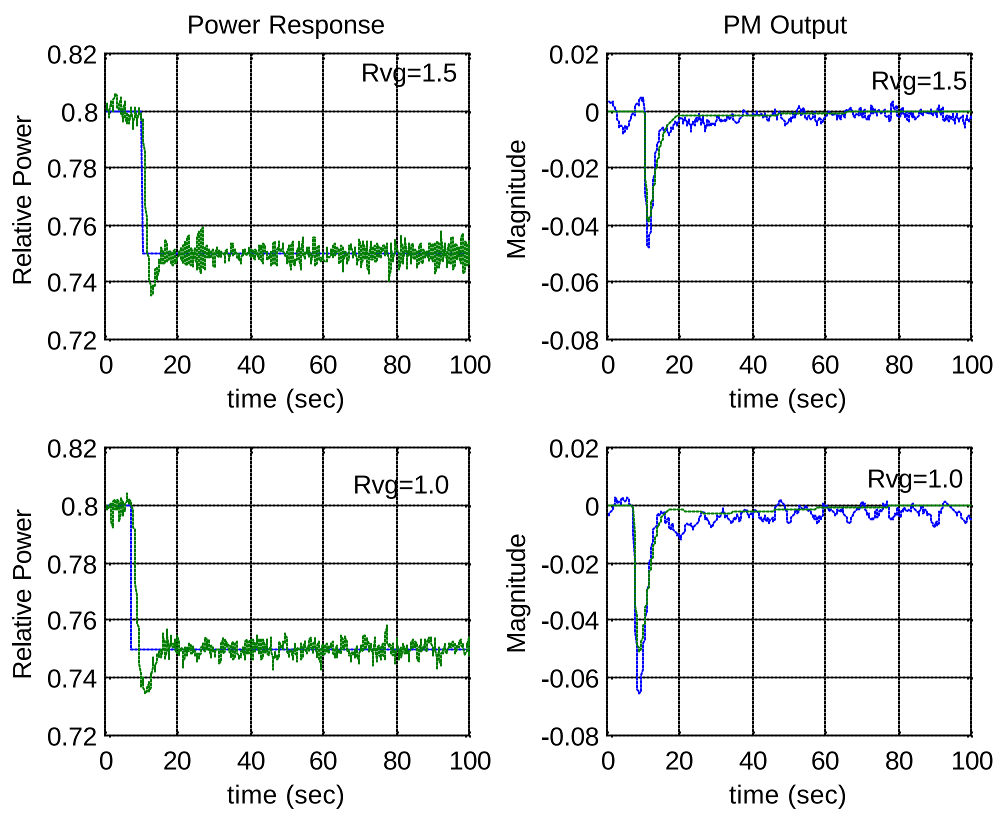
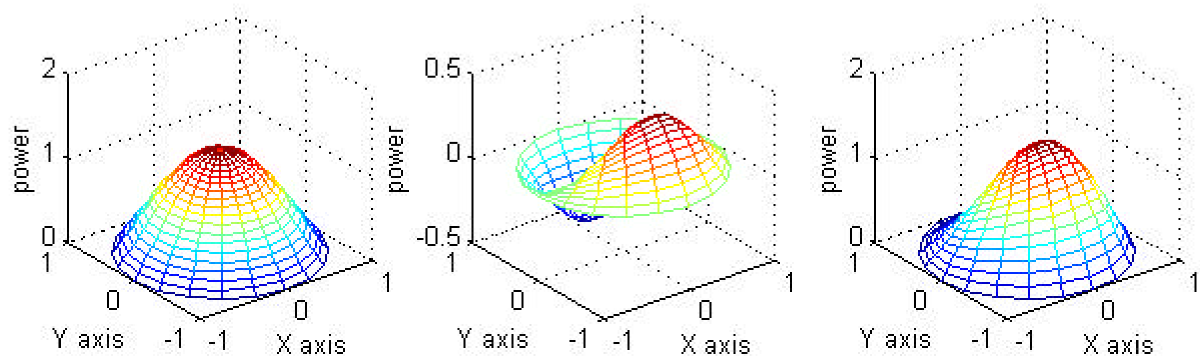


Figure 4: Experimental Results with the Controller for OR31

The second goal of Phase 2 (Task 6 in the 3-year project) was to develop real-time information displays to present the space-time dependent behavior of the out-of-phase reactor BWR stability characteristics.

A fast 3-D reactor power display of modal BWR reactor power distribution was implemented using MATLAB graphics capability as exemplified in Figure 5. Figure 5(a) shows the fundamental mode power distribution over the reactor cross-section. Figure 5(b) shows the first harmonic power distribution and Figure 5(c) shows the total power distribution over the reactor.



(a) Fundamental mode (b) First harmonic (c) Total power

Figure 5: Example of 3-D real-time information display for BWR out-of-phase (OOP) oscillation (normalized by the initial power)

Due to the large amount of computation for BWR boiling channel simulation and real-time data processing and graph generation, one computer is not sufficient to handle these jobs in the hybrid reactor simulation environment. A new three-computer setup has been identified that can efficiently address these requirements and is shown in Figure 6. The host-computer and target-computer work cooperatively under the MATLAB Real-Time Workshop environment. The principal user interaction takes place on the host computer where parameter adjustments are initiated and some elementary information displays are presented. The host-computer and target-computer are connected with network connection; it is therefore possible to separate these two computers over a relatively long distance. The hybrid BWR-simulation application code is generated in the host computer with SIMULINK and is downloaded to the xPC target option of the Real-time Workshop (target computer). The target-computer performs boiling channel thermal-hydraulic simulation and control of the Experimental Changeable Reactivity Device (ECRD) in the TRIGA reactor. The target-computer is connected to the reactor through a DA/AD card. The TRIGA reactor power is measured, and a control signal is sent to the ECRD drive mechanism to simulate the BWR reactivity feedback. Desired hybrid simulation of BWR-reactor behavior is controlled by adjusting parameters in the host-computer.

The graph computer retrieves data, both measured reactor power, which serves as the fundamental mode power of BWR, and the simulated first harmonic power from the target computer through serial cable connection. Spatial power distribution is calculated from these data and the reactor physics model in the graph computer and 3-D display of BWR reactor power of the two modes together with the total power is displayed there.

At the end of Phase 2, the graph computer and the host computer functions were implemented in the same 550 MHz computer, thus the refresh interval on the 3-D graph generation was undesirably long. A new 1.5 GHz computer will be added so that the graph functions can be executed at a desirable frequency of 10 Hz.

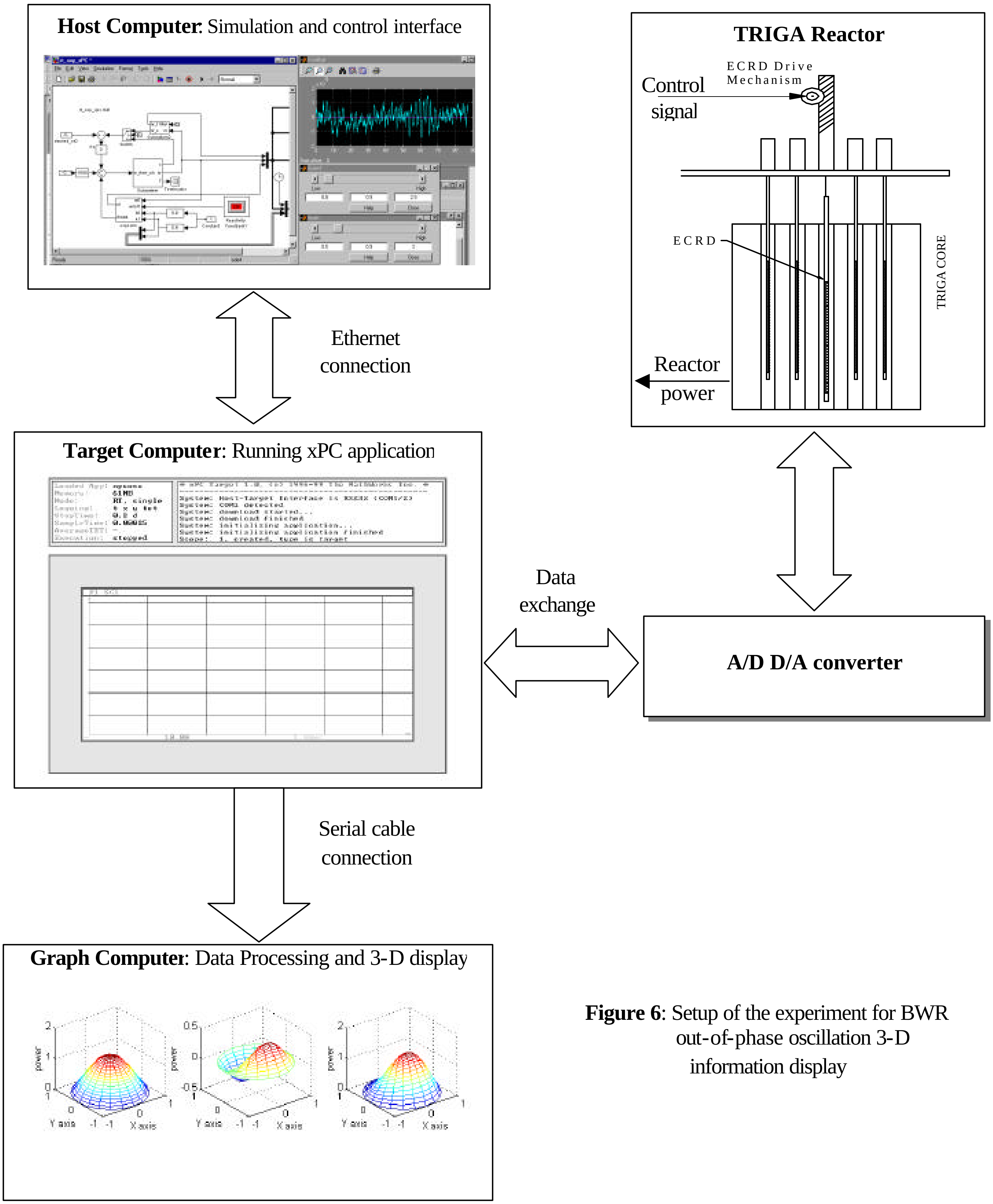


Figure 6: Setup of the experiment for BWR out-of-phase oscillation 3-D information display

CONCLUSION:

The 1999 DOE NEER-funded project on "Monitoring and Control Research Using a University Reactor and SBWR Test-Loop" has completed all of its Phase 1 and 2 goals and is ready to proceed to the next phase. Phase 3 is scheduled to run from January 1, 2001 to June 30, 2001. The Phase 3 goals are 1) develop and validate a simulation model of the testloop, which is suitable for simulation of a parallel channel for use as feedback to the first harmonic of the modal kinetics model. The HLS will then be expanded to include hybrid simulation of out-of-phase stability characteristics and 2) will implement and evaluate in-phase and out-of-phase BWR stability monitoring techniques that have been developed and demonstrated in strictly simulation environments in recent years.